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(54) Title: MACHINE CONTROLLER CALIBRATION PROCESS
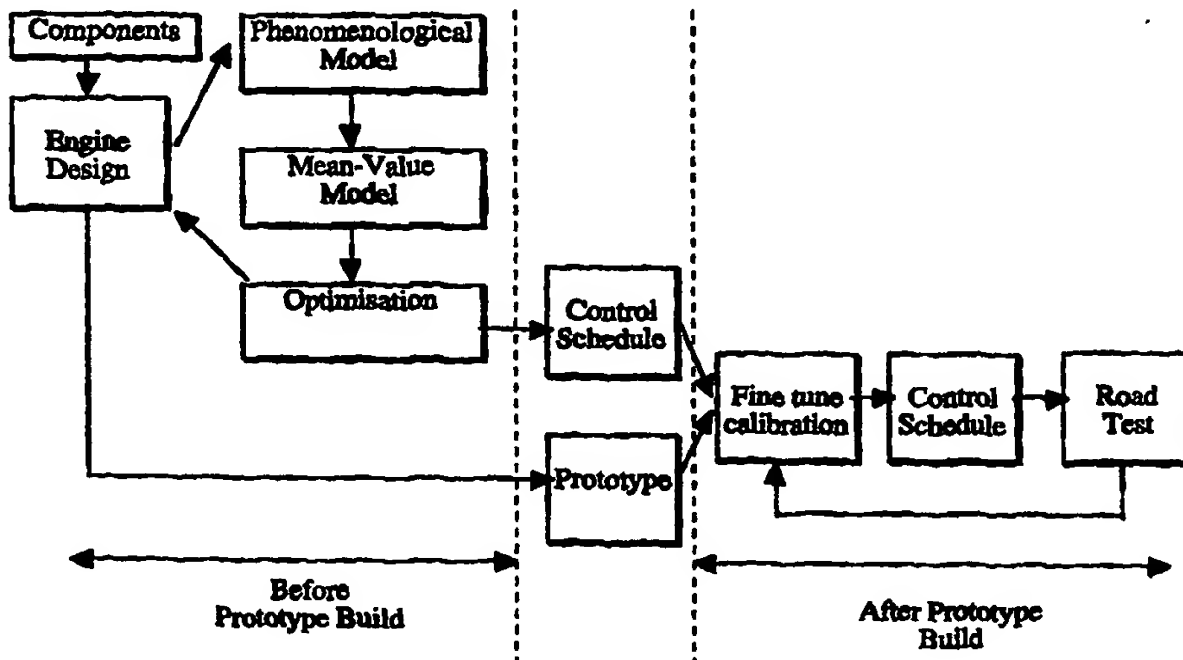
(57) Abstract

A method for deriving control parameters for a machine controller which involves using a mean–value model of the machine in a computer optimisation scheme to derive the control parameters. The mean–value model is derived from a phenomenological model of the machine.

Machine Controller Calibration Process

Field of the invention

The present invention relates to methods and apparati for
5 calibrating machine controllers. In particular, the present
invention relates to a method for calibrating a controller which
controls an internal combustion (IC) engine.

Background art

Machine controllers which work on the basis of multi-dimensional
10 look-up tables are known in the art. For example, US-A-4,489,689
discloses such a controller.

Such a known controller may have look-up tables in which each
dimension of a look-up table corresponds to a particular sensor
sensing some functional state of the machine, such that each
15 particular combination of sensor values corresponds to a unique
cell in the table. The cells of these look-up tables contain
appropriate values for the control inputs to the actuators
controlling the machine, depending on the steady state condition
of the machine as indicated by the sensor values. Additional
20 compensation may be added to the actuator values when the
machine is in a transient condition.

Before such look-up table controllers can be used to control a
particular machine, the controller must be calibrated, i.e. the
entries in the look-up table must be completed.

25 By way of example for a prior art machine design process, Fig. 1
shows a schematic depiction of a typical prior art design
process for the design and prototyping of a new engine.

A new machine design is typically built up starting from a basis
of a combination of readily bespoke parts, assemblies from third
30 parties, components from previous models of the machine and new
parts. A design is drawn up and the designers may build
phenomenological models of the intended design in order to allow
them to predict performance of the machine. It is to be noted

that although such phenomenological models are available, many designers do not use them, preferring to use more traditional approaches.

5   If they are used, such phenomenological models are generally based on the physical design characteristics of the machine being designed. Software packages exist which help designers to build such phenomenological models such as the CPower™ Matlab toolkit produced by Cambridge Consultants Ltd., Cambridge, U.K. Although extremely accurate (the best have resolutions down to
10 sub-cycle periods), these models require long calculation times.

Once the designers have designed the machine in question, a prototype is manufactured according to the design. The look-up tables of the machine controller are subsequently filled in by a manual calibration process involving skilled operators who run
15 the machine and manually adjust actuators which control the machine in order to achieve the desired performance. In a similar fashion, cell values for the look-up tables are also arrived at for adapted tables for transient machine conditions and for adapted tables which allow, for example, for ageing
20 effects or for particular environment effects, such as for meeting the various different emissions regulations of different countries in the case of IC engines. For example, for a car engine, the engine may be placed on a dynamometer test bed and the skilled operating staff would adjust the various actuators
25 (choke, throttle, ignition advance etc.) and record the appropriate values for use in the look-up table of the engine controller.

The conclusion drawn by the skilled machine calibrators is often that the particular prototype is not suitable and this
30 information is then passed back to the designers who rework the design and the original prototype is then reworked or a further prototype is built. This loop is continued until an acceptable machine in combination with an acceptable controller are produced. The prototype machine is then further tested in the
35 environment in which it is to be used (e.g. for car engine

designs, the car is road tested) and again, this often leads to iterations through the calibration process.

The prior art machine controller calibration process is very time-consuming, labour-intensive and entails the manufacture and
5 calibration of a plurality of prototype machines. The people involved in this time-consuming process are highly skilled and thus expensive. For example, in the car industry it is said that the time and costs involved in the engine controller calibration process is one of the major factors limiting the introduction of
10 new models of cars. The length of the calibration process also involves opportunity cost and has implications for market share associated with any delays at this stage in the development cycle.

The situation is compounded by ever more stringent machine
15 performance regulations, such as pollution regulations for IC engines. In order to meet these more stringent regulations, while still providing the desired functionality, manufacturers generally add both extra sensors to more closely monitor machine condition and extra actuators to effect better control (e.g. for
20 an IC engine: exhaust gas recirculators, variable geometry turbochargers etc.). Since the length of the calibration process is roughly proportional to the square of the number of control variables (i.e. sensors plus actuators), such additions dramatically increase the amount of calibration work needed and
25 the time required to complete the prototyping process.

Indeed, as the regulations become more strict and the machine control systems become more complex, manual calibration may cease to be a feasible procedure. The present state of the art does not offer solutions to this future problem.

30 In the prior art, the most-used method for reducing the length of the calibration process is to base machine design as closely as possible on previously successful designs and to initially fill the relevant look-up tables with values arrived at heuristically based on the values used in the look-up tables of
35 previous designs.

Furthermore, the accuracy of look-up-table-based control systems has an upper bound imposed by the use of the look-up tables. Although steady-state conditions are accurately represented by these standard controllers, the transient compensation schemes
5 used in conjunction with the look-up tables are far more approximate. However, machines tend to be used for large proportions of their operating time in transient states - for example, car engines used in urban driving conditions. As the test cycles used for measuring machine performance in order to
10 test for the meeting of various regulations (e.g. emissions test cycles) will inevitably change to reflect the use of a machine in transient states, contemporary controllers will no longer provide accurate enough control to meet the relevant regulations.

15 It is the general aim of the present invention to provide a method of machine controller calibration which is quicker than prior art methods and which involves less likelihood of having to rework or rebuild machine prototypes.

In particular, it is an aim of the present invention to provide
20 a machine controller calibration process which enables a model of the machine to be constructed from which control parameters for the machine controller may be derived without the need for building a physical machine prototype.

It is also the aim of the present invention to provide a machine
25 controller calibration process which enables machine designers to use more complex controller architectures such as, for example, optimal, adaptive, predictive or neuro/fuzzy controllers. Thus the present invention enables the development of better machine controllers.

30 **Summary of the Invention**

The present invention provides a machine controller calibration process for calibrating a machine controller comprising the steps of:

i)   constructing a phenomenological model of the machine;

ii)   constructing a non-parametric model of mean-value machine
        characteristics derived from the phenomenological model;

iii)   using the non-parametric model for deriving control
        parameters for the machine controller.

5   whereby, a prototype controller may be derived without the need
    for manufacturing a physical machine prototype.

In another aspect, the present invention provides a method of
producing a non-parametric model of a machine which method
involves the use of a neural network acting on the mean-value
10 machine characteristics derived from a phenomenological model of
the machine.

In a further aspect, the present invention provides a method for
deriving control parameters for a machine controller which
involves using a mean-value model of the machine, which mean-
15 value model has been derived from a phenomenological model of
the machine, in a computer optimisation scheme to derive the
control parameters.

In a further aspect, the present invention provides a method of
automating a machine controller calibration process which
20 involves using a mean-value model of the machine, which mean-
value model has been derived from a phenomenological model of
the machine, in a computer optimisation scheme to derive the
control parameters of the machine controller.

The calibration method of the present invention allows machine
25 manufacturers to meet, for instance, short-term emission
requirements with reasonable calibration times, in use in
conjunction with standard, look-up-table-based control systems.
It also enables the simulation of the machine under transient
conditions and thus enables machine designers to use the control
30 parameters derived from the model to form the basis for a more
advanced controller, such as for an optimal, adaptive,
predictive or neuro/fuzzy controller.

Essentially the present invention uses two models to represent
the machine - one faster and one slower. This approach means

that, whilst the faster non-parametric model does not contatin as much detail as the phenomenological model, it allows a very substantial speeding up of processing and can therefore be used in calibrating a machine controller or designing some form of
5 optimal controller or the like in real time.

Since the invention allows the callibration of a machine without the need for building a machine prototype, the invention allows substantial cost and time savings to a machine designer/producer.

10 Further aspects, advantages and objectives of the invention will become apparent from a consideration of the drawings and the ensuing description.

Brief Description of the Drawings

15 Fig. 1: A schematic drawing of a prior art engine design process;

Fig. 2: A schematic drawing of a engine design process incorporating the calibration method of the present invention.

20

Detailed Description

By way of example for a prior art machine design process, Figure 1 depicts a typical prior art engine design process as described above.

25 By way of example for a machine design process using the calibration method of the present invention, Figure 2 depicts a typical engine design process using the calibration method of the present invention.

The major differences between the design processes of figures 1
30 and 2 are that:

i)   the point at which the first physical prototype is built is much later in the design process of figure 2; and

ii)   the building of the physical prototype is not in an
      iterative loop in the design process of figure 2, whilst
      it is in an iterative loop in the design process of figure
      1.

5 This is achieved by using a phenomenological model of the engine
   to enable simulation in software, allowing a mean-value model to
   be constructed using, for example, a neural network (such as
   multi-layer perceptrons, Cyberko networks or radial basis
   function networks). The mean-value model is then fast enough to
10 use in a computer optimisation scheme, thus enabling the semi-
   automation of the calibration process. The constructed mean-
   value model may advantageously be a non-linear model.

   Under this scheme, when the first prototype is constructed, the
   calibration engineer will be provided with a control strategy
15 which will then merely need fine-tuning in order to compensate
   for modelling inaccuracies. The time on the test-bed is thus
   drastically reduced and both time and money are freed up for use
   on something else.

   It is to be noted that a machine controller may control only a
20 particular part of a machine and not the whole machine. Clearly,
   the current invention is also meant for use in such
   circumstances – a 'machine controller' is intended to be
   interpreted as a controller of a machine or of some sub-system
   thereof. Examples of such sub-system controllers might be for
25 controlling exhaust gas recirculation or for controlling a
   variable geometry turbocharger or for controlling electronic
   fuel injection etc.

   Once the inventive concept of this invention is understood, the
   person skilled in the art would, without the use of any
30 inventive skill, think of alternatives to the use of neural
   networks for constructing the non-parametric model. For example,
   cubic B-splines, ridge function approximators or even polynomial
   techniques are also appropriate for use in constructing the non-
   parametric model.

Claims

1. A machine controller calibration process for calibrating a machine controller comprising the steps of:

    i)   constructing a phenomenological model of the machine;

5   ii) constructing a non-parametric model of mean-value machine characteristics derived from the phenomenological model;

    iii) using the non-parametric model for deriving control parameters for the machine controller.

10 whereby, a prototype controller may be derived without the need for manufacturing a physical machine prototype.

2. A machine controller calibration process for calibrating a machine controller according to claim 1 wherein a neural network is used to construct the non-parametric model of 15 mean-value machine characteristics derived from the phenomenological model.

3. A method of producing a non-parametric model of a machine which method involves the use of a neural network acting on the mean-value machine characteristics derived from a 20 phenomenological model of the machine.

4. A method for deriving control parameters for a machine controller which involves using a mean-value model of the machine, which mean-value model has been derived from a phenomenological model of the machine, in a computer 25 optimisation scheme to derive the control parameters.

5. A method of automating a machine controller calibration process which involves using a mean-value model of the machine, which mean-value model has been derived from a phenomenological model of the machine, in a computer 30 optimisation scheme to derive the control parameters of the machine controller.

6.   The use of a method according to any of the preceding claims
      in the creation of an optimal, adaptive, predictive or
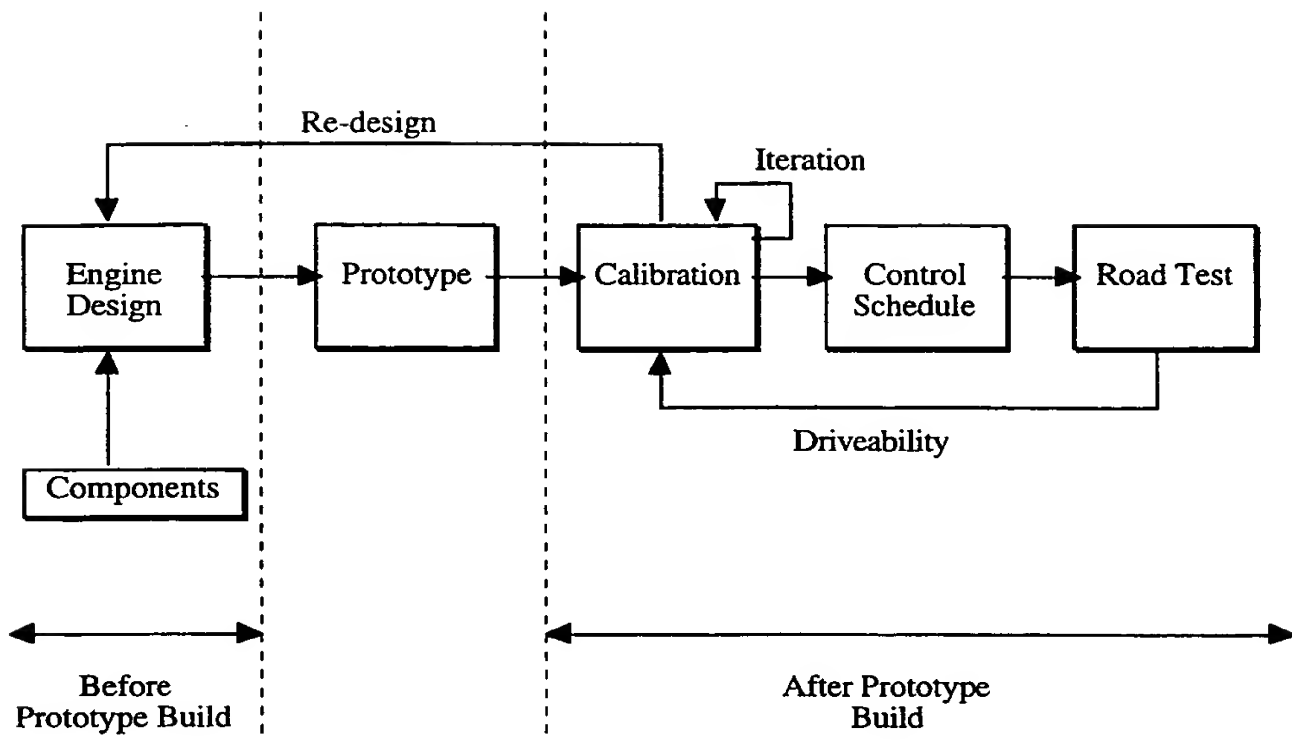   neuro/fuzzy machine controller.

5

Re-design

Iteration

| Engine Design | → | Prototype | → | Calibration | → | Control Schedule | → | Road Test |

Components

Driveability

Before Prototype Build

After Prototype Build

Figure 1

| Components |
| Phenomenological Model |
| Engine Design |
| Mean-Value Model |
| Optimisation |
| Control Schedule |
| Prototype |
| Fine tune calibration |
| Control Schedule |
| Road Test |

Before Prototype Build

After Prototype Build
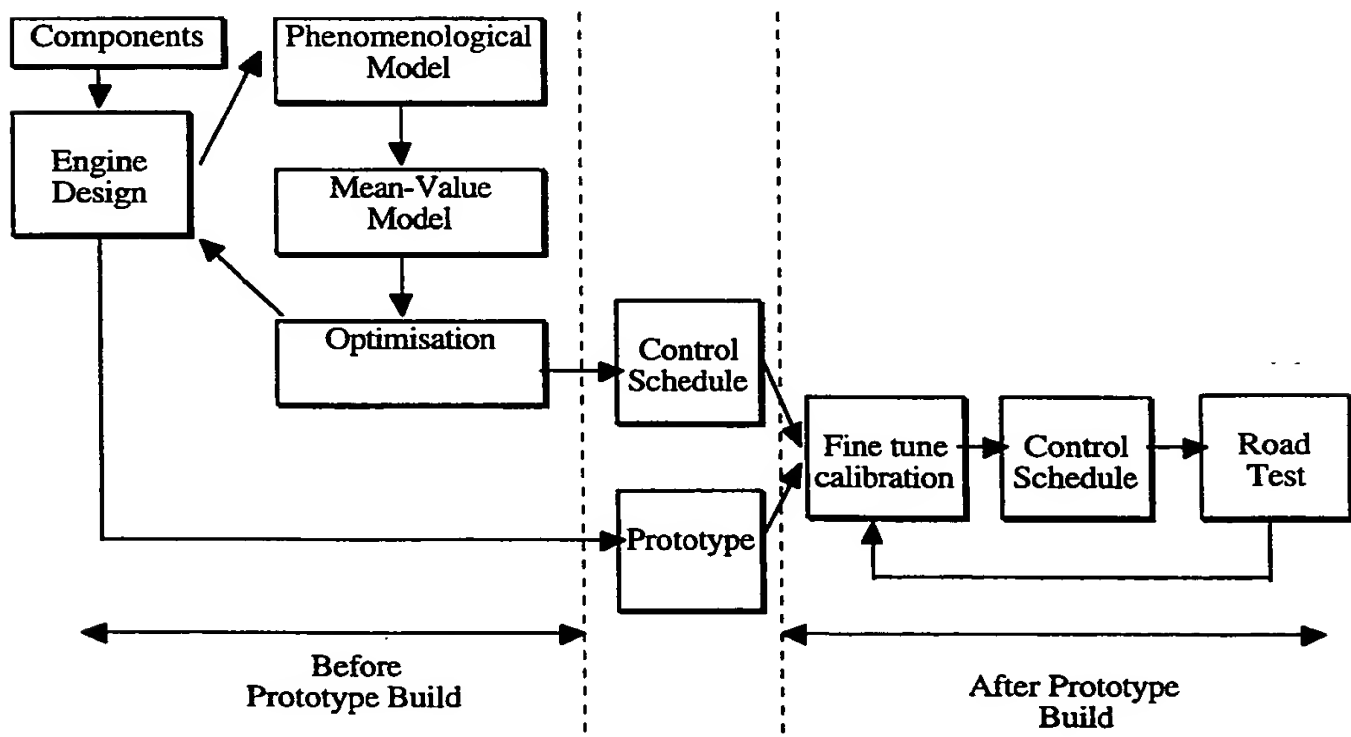
Figure 2

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   G05B17/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6   G05B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	KRAUTH J ET AL: "SIMULATION UND KUNSTLICHE INTELLIGENZ EIN UBERBLICK" IT + TI INFORMATIONSTECHNIK UND TECHNISCHE INFORMATIK, vol. 35, no. 6, 1 December 1993, pages 5-9, XP000423141 see the whole document --- -/--	1

[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
5 January 1999	12/01/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl. Fax: (+31-70) 340-3016	Kelperis, K

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	SUNG HOON JUNG ET AL: "EVENT-BASED INTELLIGENT CONTROL OF SATURATED CHEMICAL PLANT USING ENDOMORPHIC NEURAL NETWORK MODEL" PROCEEDINGS OF THE INTERNATIONAL SYMPOSIUM ON INTELLIGENT CONTROL, COLUMBUS, AUG. 16 - 18, 1994,16 August 1994, pages 279-284, XP000549590 INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS see the whole document	1,2
P,A	WO 97 42553 A (PAVILION TECH INC) 13 November 1997 see page 10, line 1 - page 18, line 19	1

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
WO 9742553	A	13-11-1997	AU	3132197 A	26-11-1997

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